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Thermal characterization of intrinsic and extrinsic InP using photoacoustic technique

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Abstract

An open photoacoustic cell operating in the low range of chopping frequency has been employed to evaluate the thermal diffusivity values of intrinsic InP and InP doped with S, Sn and Fe. The experimental set-up is calibrated by the evaluation of thermal diffusivity value of pure Si and GaAs. The present investigation shows that doped samples show a reduced value for thermal diffusivity compared to intrinsic sample. From the analysis of data it is also seen that nature of dopant clearly influences the thermal diffusivity value of semiconductors. The results are explained in terms of phonon assisted heat transfer mechanism in semiconductors.

1. Introduction

Photoacoustic (PA) effect and PA spectroscopy have been successfully applied with great elegance and effectiveness to the nondestructive evaluation of material properties [1–4]. In particular, the use of PA technique for the thermal characterization of semiconductors has attracted much attention in the context of fabrication of electronic and optoelectronic devices [5–10]. Data on the thermal properties are vital for any material that gets involved in devices with thermal dissipation. Like optical absorption coefficient, thermal diffusivity is a unique and important thermophysical parameter, which measures the rate of diffusion of heat in a material. The physical significance of this quantity lies in the fact that the inverse of thermal diffusivity is a measure of time required to establish the thermal equilibrium in the specimen. Thus the accurate measurement of thermal diffusivity of semiconductors and the study of influence of doping on the thermal diffusivity value have great physical and practical significance.

The PA effect directly looks into the heat generated in the sample due to nonradiative de-excitation processes following an optical excitation of the sample with modulated or pulsed light. During the last decade, the minimal volume open photoacoustic cell (OPC) technique has been extensively used with great convenience to evaluate thermal, optical and transport properties of semiconductors [5–10]. For semiconductors, in the thermally thick regime, where the sample thickness is greater than thermal diffusion length, the PA signal is generated due to different processes namely intraband thermalization, nonradiative bulk recombination and nonradiative surface recombination. In the thermally thick region, there are some chopping frequency ranges over which all these components are intermixed [11] and hence the evaluation of thermal parameters in this restricted range does not yield accurate result. Since phase is a relative quantity, the evaluation of material parameters from the phase of PA signal is more accurate [12]. In the present investigation, we have evaluated the thermal diffusivity value of intrinsic and doped samples from the phase of the PA signal for a frequency range ($f \leqslant (\pi/2)^2 f_c$) for which the sample thickness matches the thermal diffusion length of the sample. The advantage of using this chopping frequency range is that, in this range thermal diffusion is the only heat generation mechanism and hence the measured thermal diffusivity value is more accurate [13].

In this paper, we report the thermal diffusivity value of InP and InP doped with Sn, S, and Fe using the above approach. The experimental set-up is calibrated by measuring the thermal diffusivity value of intrinsic Si and GaAs and comparing them with the standard values.

2. Experimental set-up

The OPC used in the present experimental set-up is the standard one with some modification, the details of which have been described elsewhere [14]. The sample fixed on the OPC using vacuum grease is irradiated by optical radiation from an argon ion laser (Liconix 5300) at 40 mW with a power stability of about ±5%. The 488 nm laser beam is modulated using a mechanical chopper (Stanford Research Systems SR 540) before it impinges normally on the sample. The laser radiation is not focused so as to avoid the lateral diffusion of heat. The periodic pressure fluctuations produced in the coupling medium as a result of the heat generated due to the nonradiative de-excitations within the sample are measured using a sensitive microphone (Knowles BT 1754). The phase of the PA signal is measured as a function of chopping frequency using a dual phase lock-in amplifier (Stanford Research Systems SR 830).

The details of the samples under study are given in table 1. The samples used for the present studies are Si, GaAs, InP, InP doped with Sn, S and Fe grown using liquid phase epitaxial (LPE) method. One surface of the sample is highly polished and the other surface is roughened.

3. Theoretical model

From the one-dimensional thermal diffusion model of Rosencwaig and Gersho [15], it is seen that the amplitude and phase of the OPC signal for optically opaque samples are given, respectively, by [13]

$$A = C_0 \frac{1}{f\sqrt{\cosh(2a_s l_s) - \cos(2a_s l_s)}} \tag{1}$$

$$\Delta\Phi = -a\tan\left(\frac{\tan(a_s l_s)}{\tanh(a_s l_s)}\right) - \frac{\pi}{2} \tag{2}$$

where

$$C_0 = \frac{\sqrt{2\alpha_s\alpha_g}V_0 I_0}{T_0 l_g k_s \pi}$$

In the above expression α_i, l_i, k_i and a_i are the thermal diffusivity, thickness, thermal conductivity and thermal diffusion coefficient ($a_i = \sqrt{\pi f/\alpha_i}$) of the material '$i$', respectively. Here the subscript 'i' denotes different regions such as sample (s) and gas (g). T_0 is the ambient temperature, I_0 is the incident laser beam intensity and V_0 is a quantity dependent on the microphone characteristics.

Using the expansion in power series in terms of the dimensionless variable $x = a_s l_s = \sqrt{f/f_c}$, we obtained from equation (2), in the interval $f/f_c \leqslant (\pi/2)^2$, $\Delta\Phi$ can be reduced to next linear dependence with f such that

$$\Delta\Phi = -\frac{1}{\pi f_c} f - \frac{3\pi}{4} \tag{3}$$

We can calculate the value of f_c from the slope of the curve showing the phase of the PA signal against chopping frequency curve. The error involved in such an analysis is less than 1.2% [13]. By knowing f_c, the critical frequency at which the sample thickness matches the thermal diffusion length of the specimen, the thermal diffusivity of the specimen can be evaluated using the expression $\alpha_s = \pi l_s^2 f_c$, provided the sample thickness is known.

4. Experimental results and discussion

Figure 1 shows the PA phase as a function of modulation frequency for intrinsic Si and GaAs. From the slope of these plots we can evaluate the critical frequency f_c. The corresponding thermal diffusivity values for Si and GaAs are 0.88 ± 0.049 cm^2 s^{-1} and 0.228 ± 0.017 cm^2 s^{-1}, respectively, which agree very well with the earlier reported values (0.88 ± 0.06 and 0.228) [13, 5]. Figure 2 shows the phase of PA signal against the frequency for intrinsic InP and InP doped with S, Sn and Fe. All the curves given above have been corrected by subtracting the microphone characteristics as done by Calderon *et al* [13]. It is seen from the table that thermal diffusivity of intrinsic InP sample also agrees with earlier reported value [16]. It is also obvious from the table that doped samples show a reduced value for thermal diffusivity in comparison with intrinsic sample. For semiconductors having carrier concentration less than 10^{20} cm^{-3}, contribution from electrons to thermal conductivity is negligible in comparison with contribution from phonons. In the low chopping frequency range, PA signal is generated mainly from thermalization due to electron–phonon interaction rather than from nonradiative recombination of photo-excited carriers at the bulk and surface of the specimen. Introduction of a foreign atom into the host lattice creates more scattering centres for the phonons, which in turn reduces the phonon mean free path and hence gives a reduced value for thermal conductivity (thermal diffusivity). The lattice thermal conductivity is related to doping and temperature through the relation $k = (1/W) = AT^{-n}$ where W is the lattice thermal resistivity, T the temperature and A is a parameter which decreases with increase in doping concentration. For InP at 300 K, $n = 1.55$ [17]. The thermal diffusivity and thermal conductivity are directly related to each other through the relation $\alpha = k/\rho C$ where α is the thermal

Table 1. Thermal diffusivity value of intrinsic and doped semiconductors.

Sample	Length (μm)	Carrier concentration (cm^{-3})	f_c (Hz)	α_s (cm^2 s^{-1}) Measured	α_s (cm^2 s^{-1}) Literature
1. Si	400 ± 1	10^{18}	175 ± 7	0.879 ± 0.049	0.88 ± 0.06 [11]
2. GaAs	370 ± 1	10^{18}	53 ± 3	0.227 ± 0.017	0.228 [13]
3. InP	510 ± 1	10^{18}	53 ± 2	0.433 ± 0.016	0.44 [17]
4. InP : S	390 ± 1	10^{18}	85 ± 3	0.406 ± 0.015	—
5. InP : Sn	380 ± 1	10^{18}	85 ± 3	0.385 ± 0.016	—
6. InP : Fe	350 ± 1	10^{17}	97 ± 3	0.371 ± 0.013	—

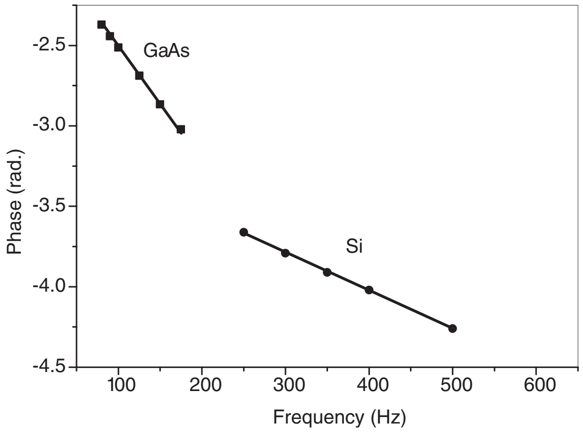

Figure 1. PA signal phase dependence on modulation frequency for Si and GaAs.

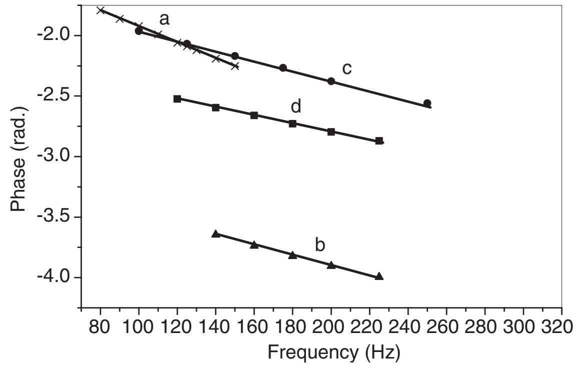

Figure 2. Phase dependence of PA signal on modulation frequency. Plots a, b, c and d represents InP and InP doped with Sn, S and Fe, respectively.

diffusivity, k the thermal conductivity, ρ the density and C the specific heat capacity of the sample. Thus a reduction in the value of k reduces the thermal diffusivity value, which explains the experimental observation on the change in thermal diffusivity for the doped sample.

It is also seen from the table that nature of dopant also influences the thermal diffusivity value. Introduction of Fe into the host lattice makes the specimen semi-insulating in nature. Besides, the introduction of Fe creates midgap energy levels, which are known to be centres of lattice relaxations and thus act as scattering centres for phonons. Hence Fe doped InP shows a lower thermal diffusivity value in comparison with n-type InP. Among the n-type InP (Sn and S doped InP), S doped InP shows a higher value for α presumably due to the smaller size of dopant. Larger size of dopant results in larger variation in potential well and hence more effective scattering for phonons and consequently a lower value for thermal diffusivity. Hence S doped InP has higher thermal diffusivity value in comparison with Sn doped InP. The influence of diffusion of photo-excited carriers on thermal diffusivity value is checked by doing the measurements under same experimental conditions but at a higher laser power level (200 mW). But the results are the same (not shown here). The surface of semiconductor wafers also has an influence on the nonradiative surface recombination. The measurements are also carried out using the other face of the specimen (polished surface). In this case also measurements yields identical results, which in turn confirms that in the present experimental frequency range, thermal diffusion is the sole source of heat diffusion in the specimen under investigation.

5. Conclusion

This paper shows that open cell photoacoustic technique under low chopping frequency range is an effective and convenient method for evaluating the thermal properties of semiconductors. It is evident from this paper that thermal diffusivity is sensitive to doping and also to the type of dopant. Since thermal properties of semiconductors are evaluated in the frequency range where photo-excited carrier diffusion is unimportant and phonon assisted heat transfer mechanism is the major process of heat transport, the signal to noise ratio is more reliable and the parameters obtained are more accurate. This paper also shows that this method is effective in evaluating thermal diffusivity of materials having high thermal diffusivity value and low sample thickness.

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